Laboratory Project Determining the Effect of Process Types on the Mechanical Properties

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Abstract

To enhance learning efficacy, improve critical thinking ability, and develop potential research interest, a mechanics course laboratory project has been improved for sophomore-level students in the mechanical engineering technology (MET) program at Purdue University's Kokomo campus. In this group project, students compare and analyze mechanical property data collected from hardness and tensile testing of ABS (Acrylonitrile butadiene styrene) specimens. The laboratory procedures and the testing specimen geometries follow appropriate standards for materials testing. The experiment includes a study on the effects of manufacturing process and plastic colorant on these properties by using two different manufacturing processes and five different colors. Based on two semesters' learning of materials and processes in their freshmen year, students are expected to test, compare, and explore the differences in property results caused by variability in the manufacturing process and material. The understanding of mechanical properties, such as resilience, yield stress, normal strain, and modulus of elasticity, is strengthened and extended beyond textbook and lecture knowledge. At the same time, this project helps students get more practice in sample production, measurement, and testing processes. Pre- and post-surveys focused on learning efficacy, research interest, laboratory experience, and team working were completed by the students. This paper presents the results of both surveys, evaluation of the discussion and conclusion sections from the students' project reports, and reflections on how the 2018 project modifications affected student learning outcomes.

Keywords: Tensile test, Hardness, Colorant, 3D printing, Specimen manufacture

Background

Hardness and tensile strength are fundamental and important mechanical material properties. College students in mechanical engineering technology program learn their knowledge of these properties (and strength of materials) from textbooks and experiments. By following ASTM standard test methods, testing for hardness and tensile properties of different engineering materials is performed by students in multiple mechanics and materials courses. A common hardness test method for a polymer is based on ASTM D785—Rockwell Hardness[1]. Tensile testing lab of plastics introduces the ASTM D638 standard method to students[2]. Generally, students have no difficulty completing these two testing labs. They measure the specimen's dimensions, set up the testing, collect appropriate data, do corresponding calculations, and complete their lab reports with a short discussion or summary. Unfortunately, the manufacturing quality of the specimen, an important contributor to the resulting testing performance, is often omitted from student reports. Without consideration of test specimen's quality, evaluation of the material properties testing is not complete and students miss the opportunity to connect practical application with theory

To extend students' learning from lecture and enhance students' awareness of experiment research work within the context of a required class, sophomore MET students in the strength of materials course experienced an intentionally designed group laboratory project on polymer's hardness and tension tests at the Purdue University Kokomo campus. The students are commuters, and the typical engineering technology class includes 6-15 students. Courses are often taught in a studio format. The campus culture tends to emphasize the efficient completion of all educational tasks performed by students.

Introduction

The objectives of the hardness test on polymers were to explore the overall hardness characteristics of polymeric specimens and interpret the relevant standard method. A Rockwell test stand, indenter, Rockwell Hardness scales, and test specimens were introduced to students for experimental work based on ASTM D785[1]. This form of hardness testing determines a material's resistance to surface penetration under a known load from the depth of the permanent indentation.

To evaluate tensile strength, testing of similar polymer specimens was conducted according to ASTM D638[2], resulting in stress-strain curves that provide mechanical material properties such as stiffness and strength.

Past sets of both laboratory reports revealed a lack of discussion of the specimen's preparation and quality in most cases. Students generally ignored the relationship between the specimen's manufacturing process and its performance. Therefore, a group lab project for the sophomore Strength of Materials course was redesigned and modified to help students link their manufacturing processes experience to mechanics course knowledge, improve scientific analyzing ability, and potentially develop an interest in experimental research. The project was initiated in 2017 and refined in 2018[3]. Other educators have shown that guided exploration of significant questions deepens student conceptual understanding and increases their knowledge retention[4]. This course, including the project, meets in a studio format which has been shown to be a preferred instructional delivery method for STEM learning (two two-hour weekly meeting times in a mixed-use environment)[5].

Designed Laboratory Project

Students were required to test and compare the tensile strength and hardness of specimens made of ABS, a common thermoplastic material. The original color of ABS is translucent ivory to white; pigment or colorant can be added to change the natural color, and potentially modifying material properties[6].With staff assistance, students manufactured the ABS testing specimens by 3D-printing and CNC machining. All the specimens were subjected to ASTM-based tensile and hardness tests. Data and results were collected, plotted, and compared in terms of variations in colorant, printing orientation, and manufacturing method.[7,8,9] The quality of samples and the limitation of each process will be discussed in detail in the results section. Students acquired experimental research experience by working through the hands-on design, processing and testing phases of the project. They made assumptions and estimations prior to obtaining experimental results or analyzing the test data, allowing them to validate or reject their initial expectations. Their conclusions incorporated recommendations for future improvements.

Methodology

Two or three students were assigned to each team. All seven sophomore students had a month to complete the project. Their laboratory activities and responsibilities included the design and fabrication of specimens, dimensional measurements, sketches, property data collection and results, comparative analysis of the results, and discussion of each varied factor (process, colorant, and printing orientation) affecting the test. Project graded elements and requirements included a pre-project survey, the final report and digital data spreadsheets from each group, a group peer evaluation form from each student, and a post-project survey that was submitted on the report due date.

Limitations

All materials used to manufacture the hardness and tensile testing specimens were purchased through common commercial suppliers. No attempt was made to guarantee the consistency or quality of their properties beyond what is typically available. Similarly, specimen dimensions were expected to meet ASTM requirements, and were not held to a tighter tolerance limit. The cut-to-size sheets and 3-D filaments were from different vendors. Both vendors offered very limited details about the material. For example, colorant weight percentages were not given.

For hardness testing, the Rockwell M scale was applied initially but produced unstable and erratic readings so Rockwell L scale was used instead. Shore Durometer A and D hardness testing was also completed by the students. Unfortunately, the A and D hardness values were inadvertently mixed together and could not be considered.

Manufacturing

CNC-machining and 3D desktop printing were the two manufacturing processes applied in this project. CNC-machined specimens in two colors were from cut-to-size ABS sheets purchased online. The 3D desktop printing ABS filaments were in five colors, with specimens printed flatwise horizontally (0°) and vertically (90°).

There were two shapes of specimens fabricated by both processing methods. Flat dog-bone specimens were produced for the tensile test and flat rectangle bars were made for the Rockwell hardness test. The hardness specimens have the same overall length and overall width as the tensile specimens with a thickness of 6-mm for all. Both specimen types are shown in figures 1 and 2.

A total of 60 tensile tests and 60 Rockwell hardness tests (each bar has five testing locations) have been conducted by all the students. Data then was combined and shared by the three groups for individual group analysis.

Figure 1: photo of 3D printed specimens

Figure 2: CNC machined cut-to-size specimens for hardness test

Table 1 – Specimen Amounts, Printing Orientations, and Colors

Process	**Color**	**For Tensile Test**		**For Hardness Test**	
CNC Machining	Black	5		1	
	White	5		1	
3D Printing		Horizontal (0°)	Vertical (90°)	Horizontal (0°)	Vertical (90°)
	Black	5	5	1	1
	Blue	5	5	1	1
	Green	5	5	1	1
	Grey	5	5	1	1
	Yellow	5	5	1	1

The 1.75mm (Diameter) ABS filament properties are listed in Table 2.Cut-to-size sheets for machined specimens were 12 x 12 inch (305 x 305 mm) square (see Table 3 for their properties). With the assistance of the lab technician, students CNC-machined the square sheets to make tensile and hardness specimens.

Table 2 – Filament Specification for 3D Printing

Printer	ABS Density (g/cm^3)	ABS Extrusion Temperature (°C)
Lulzbot TAZ 5	1.07	230-240

Table 3 – Cut-to-size Sheet Specification for CNC Machining[4]

Polymer	Tensile Strength (psi)	Impact Strength (ft-lb/in)	Mold Temperature (°F)
ABS	5100	5.20	160

Measurement and Testing

Using a permanent marker, each specimen was labeled by type and number. Specimen dimensions (length, width, thickness, tab size) were measured with digital and micrometer calipers.

Hardness testing followed, via Rockwell L hardness measurement (with spherical indenter of 0.25” in diameter and load range between 10-60 kg). Working from an end of a specimen, the first test location was at 1.1 inch (27.9 mm) inward, along the longitudinal centroidal axis. Subsequent points were spaced at 1.1- inch intervals for a total of five test locations per rectangular beam.

For tensile testing, a two-inch gauge length was marked on the specimen’s middle portion. The specimen was loaded into the grips on the tensile test machine with the extensometer placed on the gauge length marks (see Figure 3a). While the specimen was pulled to failure, the tester’s data acquisition system obtained load and deformation data. The gauge length was re-measured (see Figure 3b) for calculating the elongation and final strain. Students identified important mechanical properties such as yield strength, ultimate tensile strength, and fracture stress from their results. The engineering stress-strain curve of each test was plotted from the results, making Young’s modulus another property to consider.

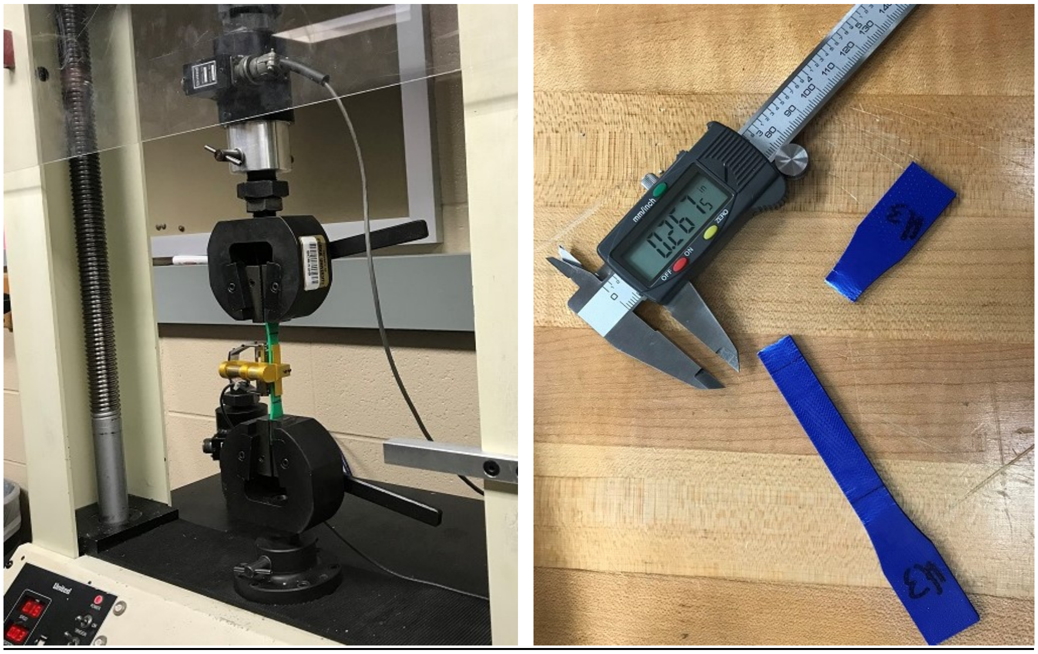

Figure 3(a) and (b): Tensile test with extensometer and digital caliper application

Results

Students compared the hardness and tensile test results by color, processing method, and 3D printing orientation. The HRL value of ABS is 74.9 according to ASTM D785. Differences between the students' experimentally determined hardness values and published data were less than 20% except for the yellow 3D printed parts, which differed by approximately 62%[10,11,12]. The experimental hardness data of the cut-to-size specimens are much closer to this value (less than 2%) while the data of 3D-printed parts range from 8%-26% in difference.

All experimental tensile and hardness data reported in figures 4 through 9 are student-reported values from the fall 2018 iteration of the class. Figure 4 shows a small difference in hardness between two colors for cut-to-size specimen (3.1%) while there is clear hardness difference by color between 3-D printed specimens in figure 5 of more than 100%. However, the difference between the cut-to-size samples' experimental value and the published data is more than 14% while the blue and black printed samples' hardness is almost the same as the published value.

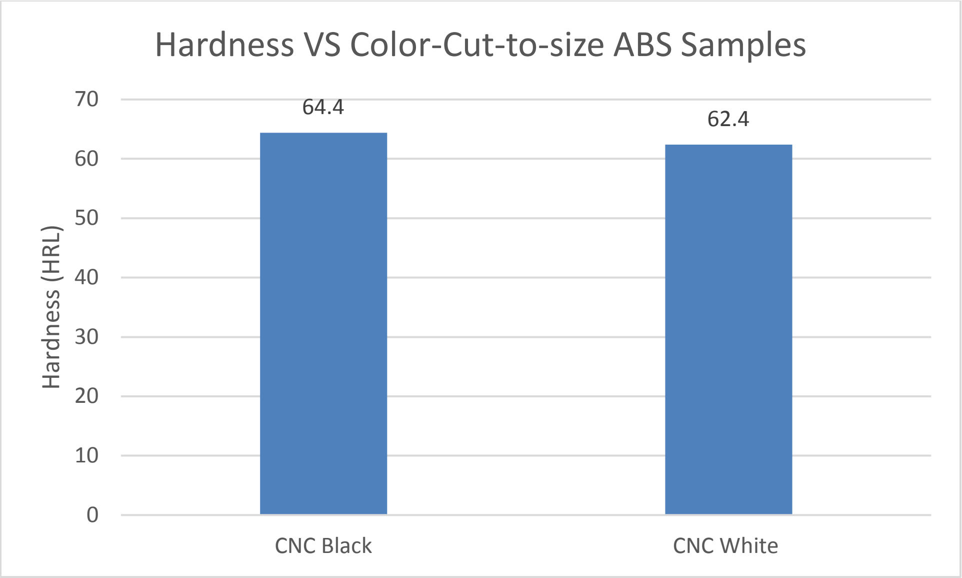

Figure 4: Cut-to-size specimens' hardness comparison by color

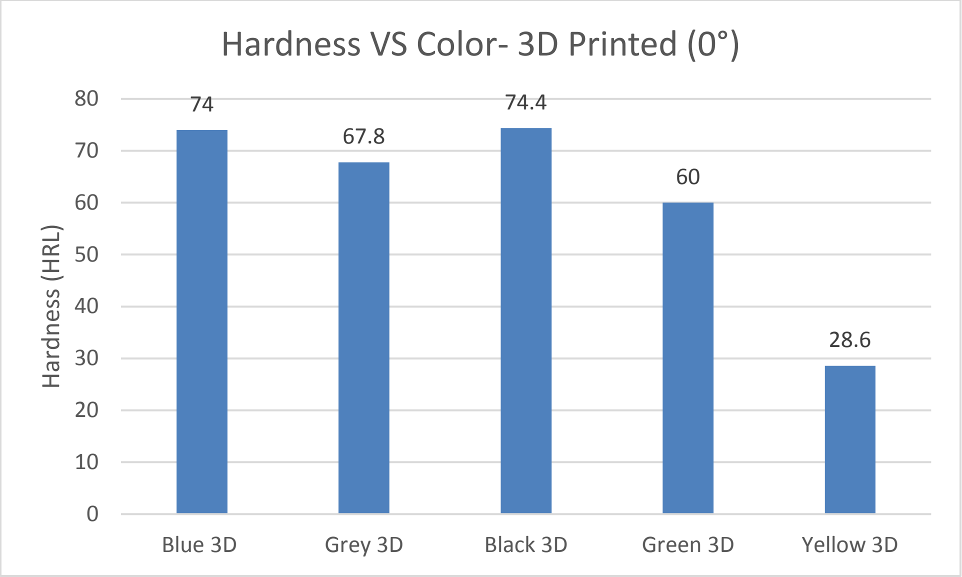

Figure 5: Horizontally 3D-printed specimens' hardness comparison by color

One published value for ABS ultimate tensile strength (UTS) is 5801 psi[12]. Figures 6 and 7 present the UTS of 3D-printed samples in different colors. The difference between the greatest and the lowest UTS value of the horizontally 3D-printed specimens was 20% while the vertically printed ones vary by 14%. Students also observed that both printing orientations show the same trend of UTS with respect to the colorants, with yellow showing the lowest UTS and blue showing the greatest UTS. As seen with the hardness comparison in Figure 4, there is a barely perceptible UTS difference between cut-to-size specimens by color shown in figure 8.

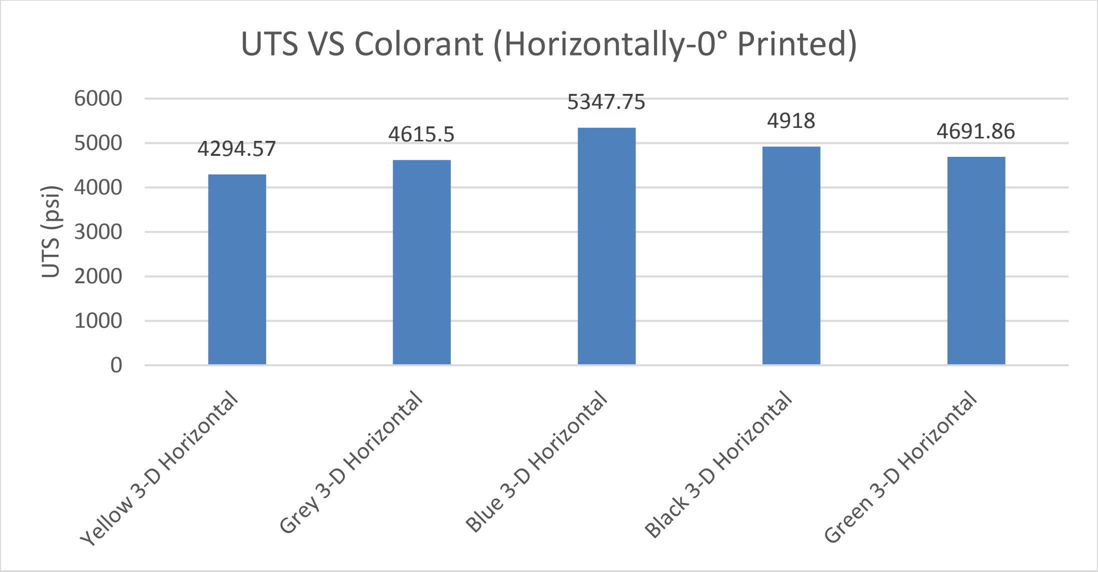

Figure 6: Horizontally 3D-printed specimens' ultimate tensile strength comparison by color

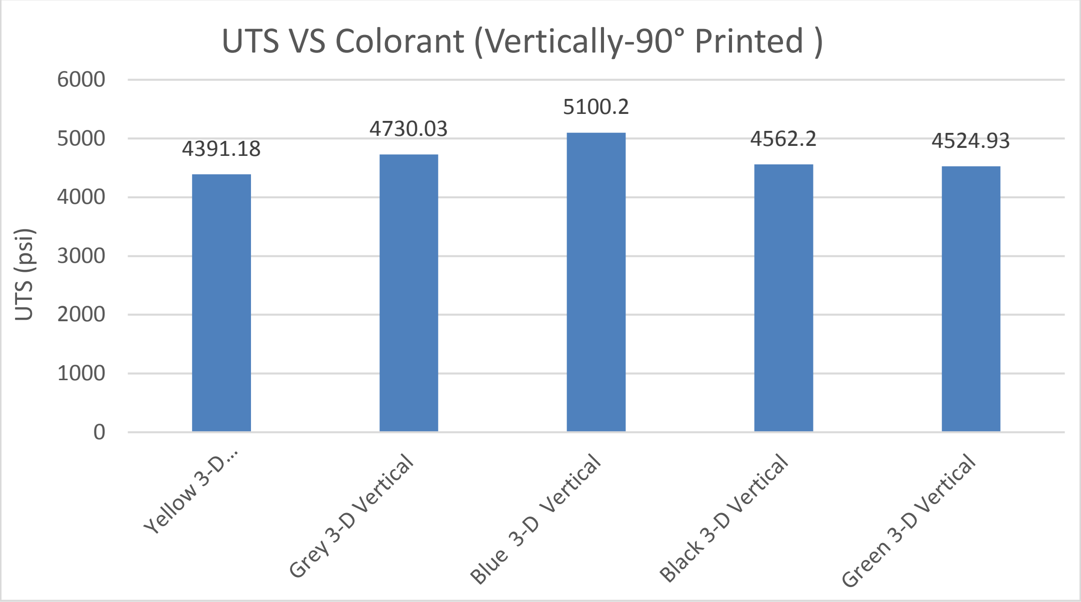

Figure 7: Vertically 3D-printed specimens' ultimate tensile strength comparison by color

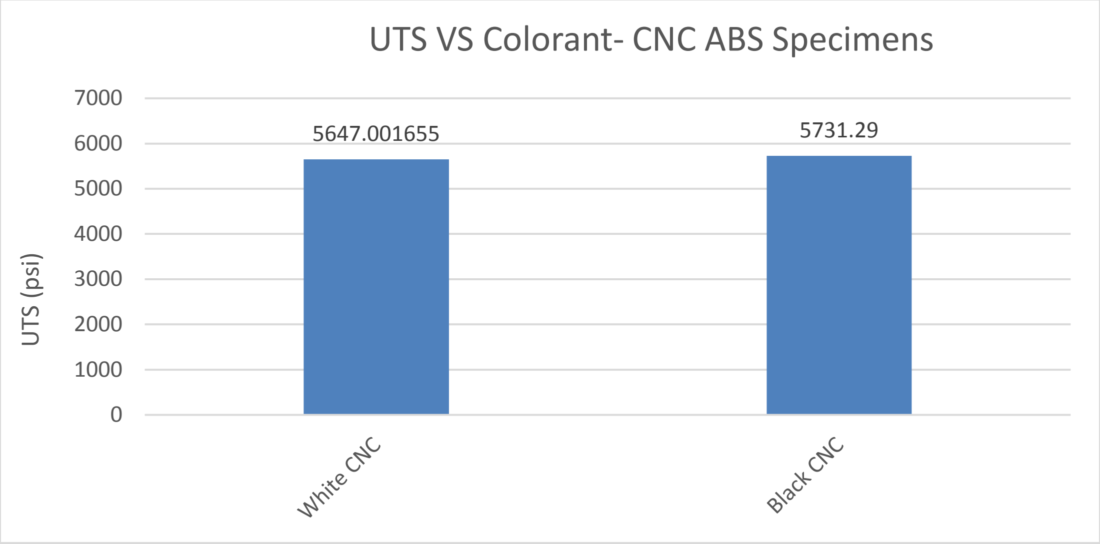

Figure 8: Cut-to-size specimens' ultimate tensile strength comparison by color

Comparing the UTS for specimens of same process but different color, Figure 8 shows about 1.5% difference.

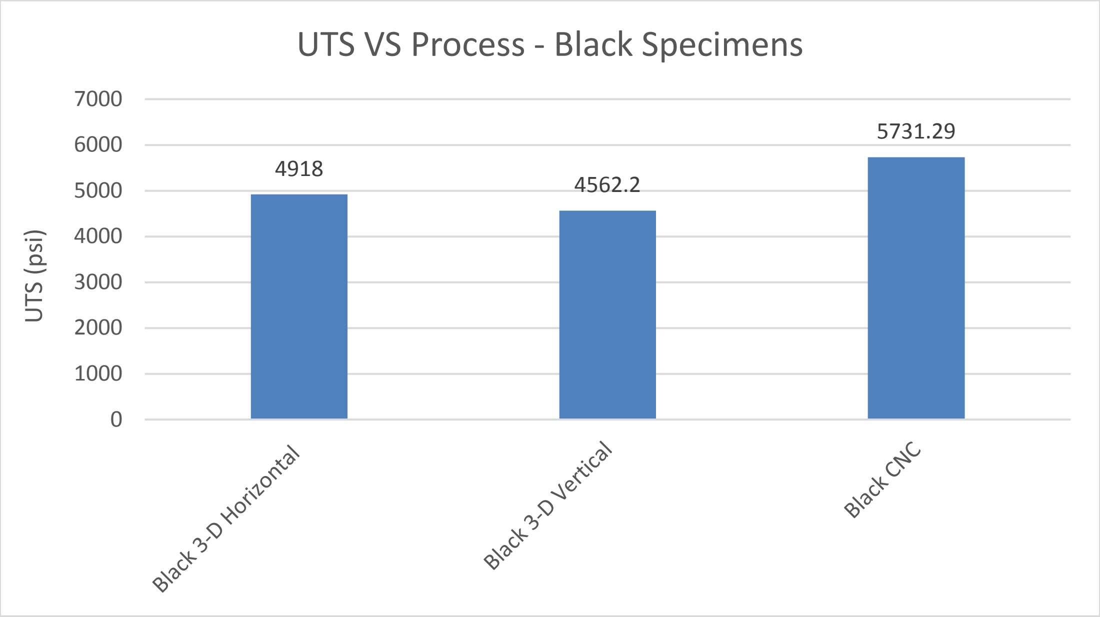

Figure 9: Ultimate tensile strength comparison by process

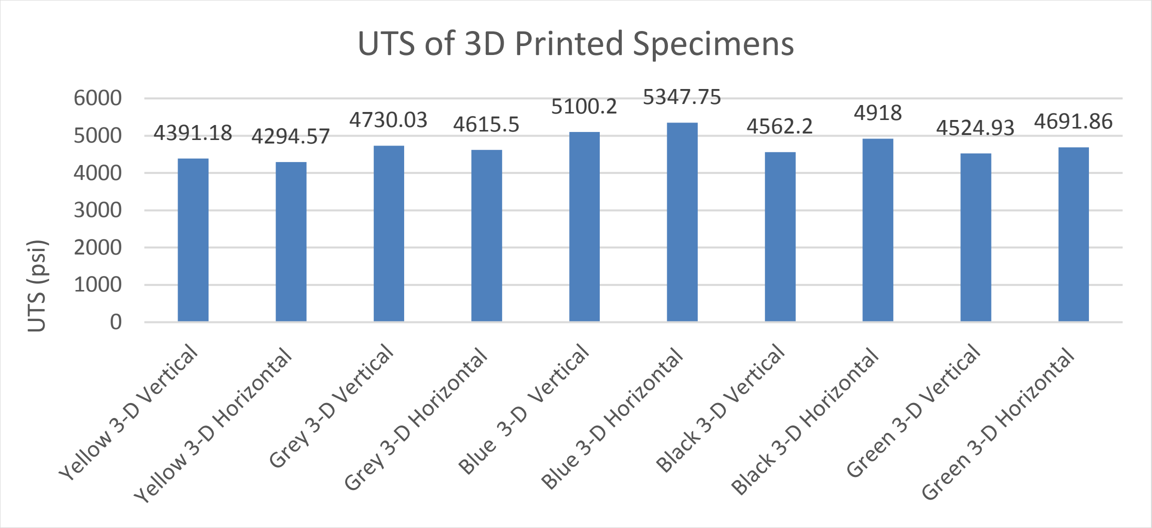

Figure 10: Ultimate tensile strength of 3-D printed specimens' comparison by color and orientation

Finally, figure 10 presents the UTS of all 3D printed part types. Unlike the hardness results, yellow parts did not have big difference in UTS when compared to specimens of other colors. Similarly, the print orientation did not generate a big difference in UTS of any color.

Since metals have strong correlation between hardness and strength, we also checked our data and found there is no direct or clear relationship existing for our polymer specimens.

Discussion

Working from their hardness and tensile test data, the sophomore MET students were able to discern that material properties are affected by manufacturing processing method and slight variations in the chemical composition of ABS. Through this project, their recognition of manufacturing sources of experimental variation was clearly presented in their reports. They pointed out that the manufacturing process did affect the mechanical properties of the material since their data showed similar results for cut-to-size specimens and significant difference between 3D-printed samples. They also mentioned that while there was clearly a difference in the property results of specimens of different colors, there was no evidence showing the property values linked to one color were superior to those of another color. . Regarding the printing orientation, the students concluded the UTS data did not show superiority in a specific orientation of print. Students recognized and commented on some differences between their preconceived assumptions of the results and the reality. For example, one group students said they assumed that the property values of cut-to-size specimens would be closer to the published data which means higher quality, but the results of hardness testing did not support their assumption.

Even though there were calculation errors and inadequate analyses in the student reports, the students still successfully proved that they have the ability to observe, explore, and seek answers through the step-by-step process designed in this project. By making assumptions, they also learned how to start the first step to accessing results. Their understanding of mechanical properties deepened, as evidenced by their project reports, and by achievement of learning objectives when compared to previous students. When evaluated for their understanding of "basic mechanical material properties … and how to apply them", 64% of the fall 2016 students met the 70% threshold of attainment by the end of the semester. The project was first implemented in fall 2017, and 78% of the students met or exceeded this threshold. Following completion of the refined fall 2018 project, 79% of the students met or exceeded this threshold. The students' self-reported views regarding queried items regarding material properties, manufacturing process effects, team project-based learning, and research increased for all, with the exception of the effect of print orientation on material properties. Table 4 and figures 11 and 12 show the distinct shift in student perspectives from pre-project to post-project. Students began the project with assumptions regarding the extent to which choice of processing method, processing specifications, and the relatively benign additive of colorant affect material properties. As shown by their responses to survey items 1, 2, 3, and 4, nearly all students realize that all of these quantities can be significant material property contributors. Similarly, the students started with some belief in the need for conducting multiple property tests at consistent test locations (survey items 5 and 6). Upon completion of the project, all students acknowledged that this level of experimental effort and control is necessary for valid test conclusions. Items 7 and 9 show that the project had only minor success at increasing student interest in research, and that students' views of technical collaboration are positive, with only a small shift toward agreement via this project. All students began and ended the project believing in the effectiveness of hands-on learning.

Table 4 Results of Pre and Post Surveys (see Appendix A for full survey items)

Question	Strongly agree/Agree		Somewhat Agree		Disagree	
	Pre	Post	Pre	Post	Pre	Post
1 Process may affect properties	71%	85%	29%	14%	0	0
2 Colorant may affect properties	71%	100%	29%	0	0	0
3 Print orientation may affect props	100%	86%	0	14%	0	0
4 Specimen quality affects props	58%	100%	29%	0	14%	0
5 Appropriate to test multiples	72%	100%	29%	0	0	0
6 Test location is important	43%	100%	0	0	0	0
7 Research intrigues me	72%	86%	29%	14%	0	0
8 Lab projects help me learn	100%	100%	0	0	0	0
9 Teamwork improves research project	71%	85%	29%	14%	0	0

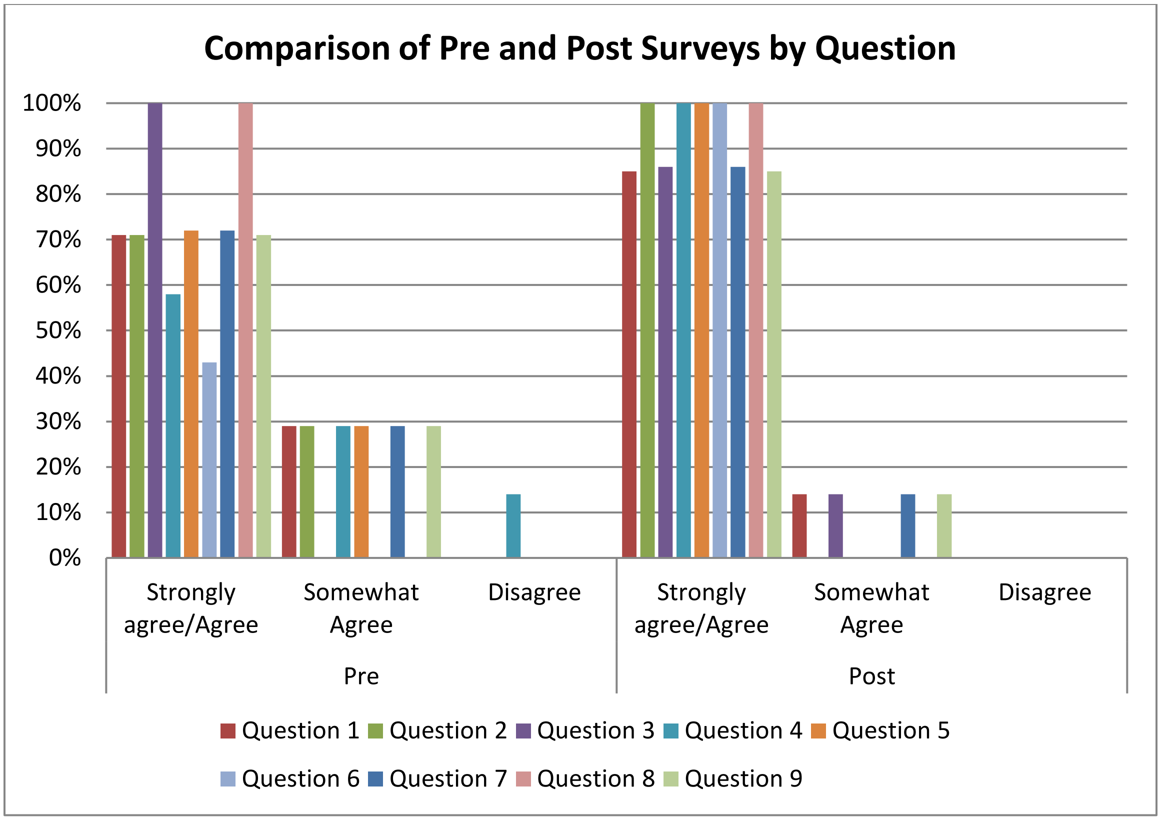

Figure 11: Student responses to pre and post-project surveys (see appendix A for survey items)

Summary

The refined laboratory project met its goals of increasing student awareness of the variability in mechanical properties based on manufacturing and enhancing their observation and understanding of experimental research. Some students also mentioned the importance of this hand-on experience which couldn't be replaced by computer simulation. The pre and post surveys show enhanced student views of research and experimental work as an outcome of this project. Their end-of-course assessments indicate a significant improvement in understanding of mechanical material properties and their application when compared to previous semesters that did not include this project. The refinements did not produce much change in student attainment of other mechanics course learning objectives, but did continue the learning gains seen with the project's initiation while strengthening their views of experimental research.

However, lack of the colorant information (resin type and percentage in usage) in the 3D-printing filaments limited the extra analysis of the colorant influence to the mechanical properties and the accuracy of the testing data. In the future, plastic colorants could be purchased and added in raw polymer pellets to inject mold the sample specimens for testing. And there was not sufficient property determination practice in this lab project. Students will be expected to compare the calculated modulus of resilience, toughness, and Young's Modulus to the published data in the next updated project, as well as tensile strength, Rockwell hardness and Shore Durometer A and D.

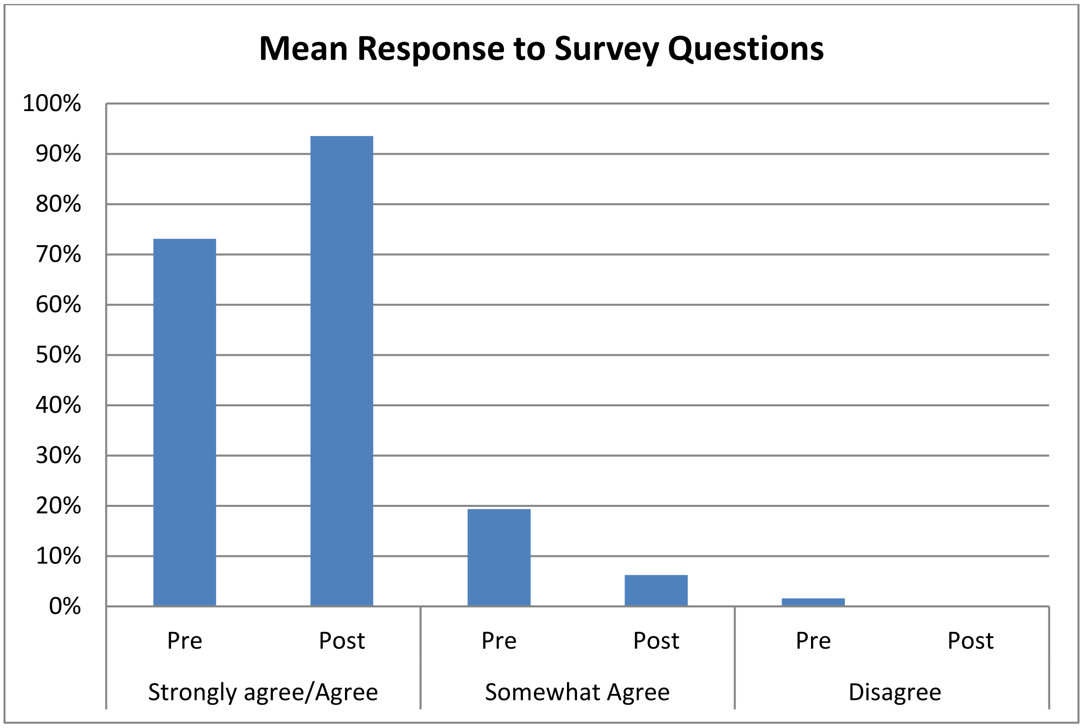

Figure 12: Mean shift in student responses from pre- to post-project survey

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Appendix A: Survey items

(Likert scale, 5 choices from strongly agrees to strongly disagree).

1. I understand the manufacturing process may affect the hardness, tensile strength, and stiffness of a material.
2. I understand the colorant may affect the hardness, tensile strength, and stiffness of a material.
3. I understand the 3-D printing orientation may affect the hardness, tensile strength, and stiffness of a material.
4. Specimen quality affects material properties.
5. The ASTM requirement for testing multiple identical specimens is appropriate when determining material properties.
6. Establishing consistent test locations across specimens is important.
7. Experimental research intrigues me.
8. Hands-on lab projects help me to learn and understand course knowledge.
9. Working with other students on a team improves my research project experience (when compared to doing an individual research project).
10. Comments

Appendix B: Polymer suppliers

1. Filament material supplier webpages
   ABS page: https://www.matterhackers.com/store/3d-printer-filament/abs
2. Cut-to-size Plastic Sheeting
   https://www.tapplastics.com/product/plastics/cut_to_size_plastic/abs_sheets/524